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The Differential Effects of Competitive University Funding on Production Frontier and Efficiency

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Abstract

This paper develops a theoretical framework for the impact of competitive university funding, suggesting that the direction of the effect might differ between the production frontier and efficiency. We test the models predictions using a panel data set at micro-level across eight European countries to estimate a simultaneous two-stage stochastic frontier approach. Supporting our predictions, the results show that tuition fees have a positive impact on the production frontier, but a negative one on efficiency. Conversely, public international funds reduce the production frontier, but increase efficiency. These findings suggest that introducing competition in the university sector entails a trade-off that should be taken into account by politicians.

Keywords: Stochastic Frontier Analysis, Production Frontier, Efficiency, University, Third-Party Funding

JEL-Classification: I22, I23, I28

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1 Introduction

Universities face substantial pressure to use their funding in an efficient manner as public and private agencies tend to provide financial resources based on competitive funding. Besides, universities have become increasingly important as part of the national innovation system. Consequently, the interest to measure and evaluate university productivity has increased substantially by both the university management and the politics. But there are few articles analyzing the impact of different funding resources on productivity of universities. However, both the theoretical and empirical findings are ambiguous, indicating that further research in this area is required to allow policymakers to make evidence-based decisions (see e.g. Van der Ploeg and Veugelers, 2008).

Our paper attempts to analyse the effects of competitive funding on university production. Thereby, we focus on the production frontier, which is build by the best performing universities, whereas deviations below from such a 'best practice frontier' implies inefficient production. The question arises, are the effects of competitive funding on the production frontier and on the inefficiency the same? Based on the framework of principal-agent-theory with the donor of third-party funds as the principal and researchers as the agents (see e.g. Kivistö, 2005), we consider different channels through which third-party funding might influence a university's production. To our best knowledge, there is no study which explicitly estimates the differential effects of third-party resources. Indeed, as our study is based on stochastic frontier analyses, enables us to disentangle the effects, i.e. how third-party funding especially influence both the production frontier and the inefficiency.

We extend the existing literature by analysing the impact of three competitive funding types on the university production frontier and the efficiency using a simultaneous two-stage approach for the analyses. In particular, this paper develops a theoretical framework for the impact of competitive university funding, suggesting that the direction of the effect might differ between the production frontier and efficiency. We chose the following three different funding resources—tuition fees, public international funds and private funds—as they belong to the main financial sources beside the university core budget. Moreover, we explicitly account for the multi-input, multi-output production process of higher education while applying a distance function approach. In addition, our estimations are based on a rich micro-level panel data set covering the period of 1994-2006 across eight European countries.

The panel structure of the data further enables us to tackle unobserved heterogeneity and reverse causality while introducing several control variables in our analyses.

Supporting our predictions, the results show that tuition fees have a positive impact on the production frontier, but a negative on university efficiency. Conversely, public international funds reduce the production frontier, but increase efficiency. The results for private funds are ambiguous as they indicate an inverse u-shaped effect on both the production frontier and efficiency. Our findings suggest that introducing competition in the university sector entails a trade-off that should be taken into account by politicians.

The paper is structured as follows: In Section 2 we discuss the theoretical framework our analyses are based on. The estimation approach along with the specifications of the applied models are introduced in Section 3 and Section 4. Section 5 provides information on the data used for the analyses. Estimation results of the empirical analyses are presented in Section 6 followed by conclusions in Section 7.

2 Theoretical Framework and Previous Research

In the following section we develop a theoretical framework regarding the production frontier and efficiency of universities; in other words, the difference between the impact on university's productivity of the best and the average university. It is based on the principal-agent framework with the donor of third-party funding as the principal and researchers as the agents (see e.g. Kivistö, 2005). The principal-agent problem in science (Van der Meulen, 1998) reflects a situation in which the government or a governmental private or agency is attempting to increase public research funding programs following the societal targets to enhance the national innovation system. However, as it does not come with the appropriate know-how and respective human resources to conduct the target, it needs to delegate the actual implementation of research to specialized organizations such as universities (Auranen and Nieminen, 2010). Given different utility functions between the donor of third-party funding and the agent, information asymmetries between both actors arise. Hence, the principal needs both appropriate selection and control mechanisms, which ensure that the principal's targets are fulfilled. Based on that, we consider different channels through which third-party funding might influence a university's production. We differentiate between the administration effect, the missallocation effect, the discipline and the sorting effect. They are introduced in more detail as the following.

The most apparent channel may be due to the administrative effort third-party funding induces; i.e. the acquisition of external funds requires the investment of time and money by the researchers—see e.g., the need to follow formal requirements when applying for third-party funding and to submitting interim and final reports. Therefore, as Van der Meulen (1998) points out, such monitoring systems bring additional costs, and self-reporting by the agents is unreliable without further incentives. We call this channel administration effect and assume that it results in a decrease of the production frontier due to costs of monitoring the agent's behaviour. In other words, since all universities apply for third-party funding—regardless of the extent of third-party acquisition—, these cost reduce the productivity of all universities equally, and hence only the frontier, but not efficiency is affected. In a comparative interview-based study of experimental physicists working at Australian and German universities Laudel (2006) shows that the researcher's criteria for selecting funding agencies indeed refer to the effort caused by writing a grant application and the further report procedures, and a rough success rate for getting external funds. For example, funding from the European Union was perceived as being extremely bureaucratic concerning application and reporting procedures, though a very low success rate.

The second channel, which we call the misallocation effect, arises due to the difference in the utility functions of the principal and the agent. In order to control the agents' behavior the principal has an interest to set respective restrictions concerning the use of third-party funds. However, these restrictions are based on incomplete information the principal faces and hence may cause behavioral changes and a suboptimal outcome. Finally, the misspecified restrictions will lead to a decrease of the university's production frontier as financial resources are inappropriately allocated by the principal (see e.g. Schiller and Liefner, 2006). Thereby, it is the same argument as for the administration effect, i.e. since all universities apply for third-party funding the costs due to the misallocation effect reduce the productivity of all universities equally, and hence only the frontier, but not efficiency is affected. Especially, since introducing instruments according to implement the concept of New Public Management (NPM) in the public sector, there are several studies that

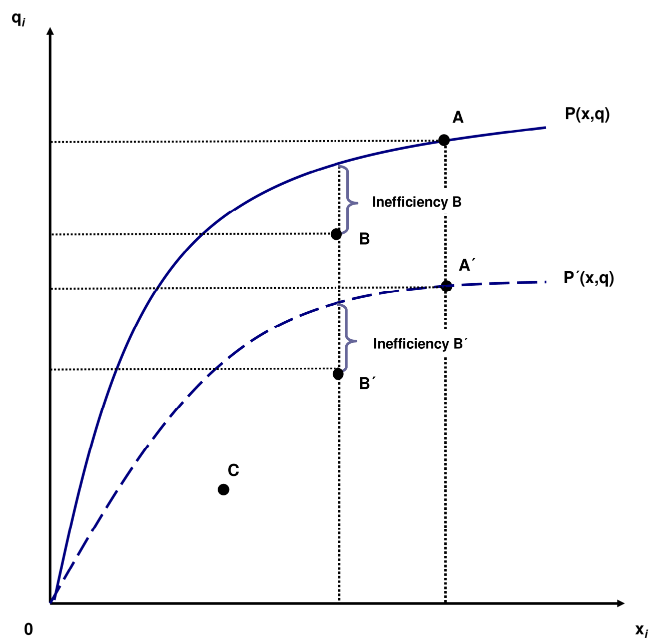

Figure 1: *Administration and misallocation effect on production frontier*

analyses the relationship of restrictions and university production. For example, Schubert (2009) finds a significant relationship between the introduction of NPM government schemes and productivity. Further empirical evidence is given by findings of Aghion et al. (2009), who present macroeconomic evidence for the misallocation effect by showing that autonomy and productivity are positively related. Kempkes and Pohl (2008) also find evidence for the misallocation effect in their examination of German universities by showing that independence increases university efficiency. Moreover, Mensah and Werner (2003) and Kuo and Ho (2007) study funding restrictions directly. Their findings show a negative correlation between (financial)autonomy and efficiency, which can be interpreted as evidence for the misallocation effect.

To illustrate the administration and missallocation effect, which both to be assumed to influence university's production frontier in the same direction, Figure 1 displays the relationship graphically. The vertical axis shows the aggregated vector of university output, (q_i), i.g. at least teaching and research measured e.g., by the number students or graduates and the number of publications, and the horizontal axis shows an aggregated input vector,

(x_i), measured in monetary terms such as operating expenses or the number of personnel based on full-time-equivalents. $P(x, q)$ shows the production frontier, and therewith represents the input-output-combinations of the best performing universities. For example, a university that produces at point A uses inputs best possible to produce outputs. Hence, it is identified as fully efficient and operates on the production frontier. By contrast, a university that produces at point B uses an input-output-combination that implies potential improvements to increase efficiency. Here, the inefficiency is displayed by the distance between B to the frontier. The misallocation and administration effect can be shown by shifting the production frontier below, $P'(x, q)$. We particularly assume that misspecified restrictions set by the principal and costs due to monitoring the agent's behavior have an negative impact on the production of universities. While holding all other factors constant a decrease of the production frontier does not affect the (in)efficiency of point A and B, i.g. A is identified as best performing university as before and operates on the frontier, while B operates below the frontier implying a substantial potential to improve its efficiency.

Based on the same information asymmetry as the misallocation effect causes, there might also be a positive impact of restricting external funds due to moral hazard. The restrictions on the employment of provided resources might decrease the ability of the agent to pursue his own goals at the expense of the donor. It will lead to using funds in an inefficient way (see e.g. Niskanen, 1971, 1975). This third channel, which we call discipline effect, results in an increase of efficient production. Van der Meulen (1998) shows, for instance, possibilities the principal has to induce competition for third-party funding e.g., peer review procedures, targeted funding or performance measures. Furthermore, if the allocation of funding resources related to the output, Auranen and Nieminen (2010) argue, it creates a general incentive for all the actors to achieve better results in order to become more competitive. Hence, we assume that an increasing competition of funding sources might decrease inefficiency. Empirical findings for such a discipline effect are provided by for instance Butler (2003), whose study shows that the introduction of competitive funding based on output counts has increased the share of Australia's ISI publications despite declining resources, indicating the presence of a disciplining effect. Again, the findings of Cherchye and Abeele (2005) find a positive correlation between the share of scientific research grants and efficiency, but a negative effect of contract research funds.

The respective relationship is shown graphically in Figure 2. As a univer-

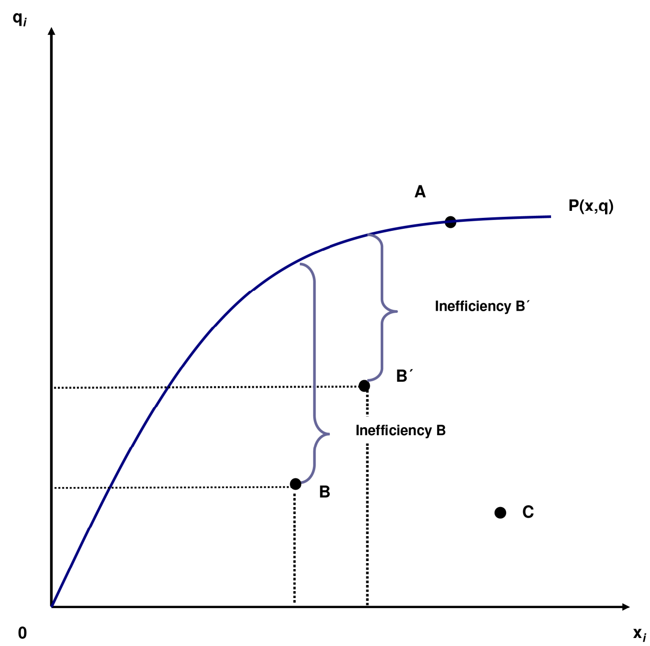

Figure 2: *Discipline effect on efficiency*

sity like at point B is to oblige to follow the restrictions on the use of competitive third-party funds the rising competition of funding sources might force B to reduce inefficient production. As a result, the distance between B', new input-output-combination, and the production frontier is decreased. Note, that a university at point A is assumed to produce as best practice university at the frontier. In other words it already competes for financial resources against other higher education institutions on the national and international market. Though, one might consider that competition of third-party funding might also lead to increased efficiency of those universities that produces on the frontier, we assume—if at all— only a small but in general no substantial change in the efficiency level (not displayed in Figure 2).

Finally, there might also be a forth effect due to a sorting of personnel and students into universities according productivity. In particular, Coupé et al. (2003), who investigated incentive effects at US economics departments find such a sorting effect for scientific personnel. Their results suggest that the more productive professors will be allocated with the more productive universities during their careers. The same is true for students as top stu-

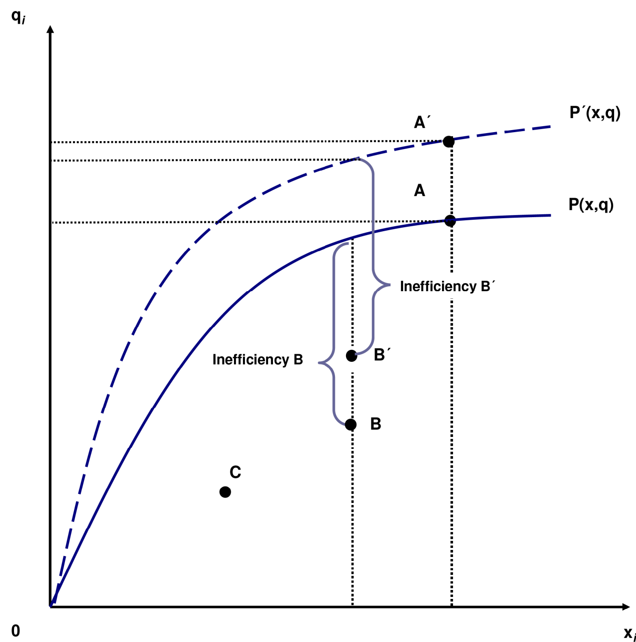

Figure 3: *Sorting effect*

dents are sorted to universities with best reputations, the most prestige, and the greatest past success of matriculating high potential students (Cook and Frank, 1993)—whereas e.g., a high ranking position usually serves as performance signal. The empirical results by Black and Smith (2004) support this argument. They found out that higher ability students disproportionately attend higher quality colleges. Based on these findings, we assume that the productivity of the best universities increases but decreases for the worst. In particular, the first are able to attract and hence select high ability personnel and students. Following this kind of downward spiral universities, which operate below the frontier, have the drawback that they can now select only from the pool of the remaining personnel and students. Due to the selection of high potentials in favor of the best performing universities, the sorting effect will further induce a rising spread between universities that operate efficiently and inefficiently, respectively.

This relationship is displayed in Figure 3 where the production frontier $P(x, q)$—again built by the best performing universities like at point A—is shifted outwards. In addition the inefficiency of a university in point B rises as the distance to the frontier increases. Given only a small number of universities that built the best practice frontier, the majority of universities operates below the frontier. Therefore, we assume that the average efficiency decreases because of the increasing variation of best and worst performing universities.

The hypotheses following the theoretical framework we developed for our analyses in order to specify the impact of third-party funding on the universities' production frontier and efficiency are summarized in Table 1:

int. public and private funds	Dis	Mis	Adm	Sort	Total
production frontier	0	-	-	+	?
efficiency	+	0	0	-	?

tuition fees	Dis	Mis	Adm	Sort	Total
production frontier	0	0	0	+	+
efficiency	+	0	0	-	?

Table 1: *Summary of third-party effects on production frontier and efficiency*

In particular, for international public and private funds we assume that a negative effect on the production frontier might be caused by a misallocation and/or an administrative effect, and a positive effect due to sorting effect. By contrast, following the theoretical framework we developed the sorting effect might have a positive impact on the spread between best and worst performing universities, and hence might result in a decrease of the average efficiency over all universities. However, we suggest a positive effect of international and private funds on efficiency arisen by an increasing competition that discipline to efficient production. For tuition fees, we predict also a positive effect on the efficiency due to the discipline effect, but a negative one caused by the sorting effect. Again, there might also be a positive impact on the production frontier due to the sorting effect. But no administrative effect is apparent because the monitoring costs are covered by the parents, and the voting by feet methodology does not create a misallocation effect.

3 Methodology and estimation approach

In order to analyze the effect of competitive funding on higher education production, this study is based on a distance function approach proposed by Shephard (1953, 1970) using a parametric efficiency measure called stochastic frontier analyses (SFA). In contrast to other representations, the distance function approach allows us to model a production process of multiple-inputs and multiple-outputs which is the case for higher education production without any underlying assumptions on specific behavioral objectives (e.g. cost minimization or profit maximization). Instead, by modeling the distance from the production frontier as a function of the vector of inputs used, x, and the level of outputs produced, q, giving a feasible production set allows us to identify 'best practice' production.

With respect to the characteristics of the production technology, a distance function may be specified with either an input orientation or an output orientation depending on the assumption whether inputs or outputs are determined by exogenous factors. While an input oriented distance function aims at identifying how much the input vector may be proportionally contracted holding the output vector fixed, considering an output oriented distance function means searching for the largest proportional expansion of the output vector given a fixed input vector. Following Abbott and Doucouliagos (2009), we utilize an output distance function. In other words, universities are modeled as output maximizing institutions, an assumption that appears reasonable as inputs of public higher education institutions are mostly decided upon by politicians.

Considering an output oriented production technology the distance function provides information on how much the output vector can be proportionally increased holding the input vector fixed. Following Coelli et al. (2005), the output distance function is defined on the output set, $P(x)$, as:

$$D_o(x,q) = min\,\{\theta : (q/\theta) \in P(x)\} \tag{1}$$

where $P(x)$ represents the set of all non-negative input vectors $x = (x_1, ..., x_K) \in R_+^K$ that can produce the non-negative output vector $q = (q_1, ..., q_M) \in R_+^M$. Then, the distance from the firm's output set $P(x)$ to the production frontier is given by $D_o(x,q)$. Färe and Primont (1995) showed that $D_o(x,q)$ holds the properties of non-decreasing, positively linearly homogeneity and convexity in q, and increasing in x. θ is the scalar distance by which the output vector can be deflated (see e.g. Coelli, 2000) and can be interpreted as the level of efficiency. If $q \in P(x)$, then $D_o(x,q) = \theta \leq 1$ which means that the distance function, $D_o(x,q)$, will take a value which is less than or equal to one if the output vector, q, is an element of the feasible production set, $P(x)$. In particular, if the output vector q is located on the outer boundary of the output set— the production frontier—, firms are identified as being fully efficient, while values less than one belong to inefficient output vectors below the production frontier.

Based on the distance function approach we employ stochastic frontier analysis (SFA) to estimate how competitive funding may affect universities' production frontier and efficiency. The theory of stochastic frontier production functions was originally proposed by Aigner et al. (1977) as well as Meeusen and van den Broeck (1977). Unlike non-parametric efficiency measures such as data envelopment analyses (DEA), which lack common statistical properties because the production frontier of 'best practice' is obtained by linear programming and therewith all deviations from the frontier are assumed to be the result of technical inefficiency, SFA is a parametric efficiency measure. That means it has the benefit that it accommodates to statistical noise. In particular, the production function is estimated with the underlying assumption of a composed error term, $\epsilon = \nu - u$. For a single output case the production frontier is formulated as:

$$q_i = \quad \beta' x_i + \epsilon_i, \qquad where \quad \epsilon_i = \nu_i - u_i$$

where q is the output and x a vector of the inputs of firm i. In the composed error term (ϵ), the two-sided error components, ν_i, account for statistical noise typically due to measurement errors and is normally distributed with zero mean and constant variance, i.i.d.($\nu_i \; N[0, \sigma_\nu^2]$)]. They are denoted to as the 'two-sided' error terms as they are symmetrically distributed around the 'true' frontier. Instead, the u_i components, assumed to be independently distributed of ν_i, are non-negative random error terms, $u_i \geq 0$, and associated with technical inefficiency. As they are truncated below by the frontier itself, they are often referred to as the 'one-sided' error terms. There are several assumptions how the u_i components are distributed, whereat the choice of the distributional specification is a matter of computational issues as well as theoretical considerations (see e.g. Coelli et al., 2005).[1]

Due to the parametric nature of stochastic distance functions, it is necessary to determine the relationship between inputs and outputs by specifying the functional form for the underlying production technology, and it requires assumptions concerning the distribution of the error and inefficiency term. However, adopting a translog functional form reduces the first problem substantially. Unlike a Cobb-Douglas function, which assumes for all firms elas-

[1] see for more information on distributional specification (see e.g. Coelli et al., 2005; Fried et al., 2008).

ticities of production and scale properties to be constant and the elasticity of substitution to be equal to unity, the translog function does not impose such restrictives. Instead, the translog function provides a second order approximation of the true function as cross-terms are included in the log-linear form. Therewith, it is preferable to a Cobb-Douglas function because it represents a relatively flexible functional form (Coelli et al., 2005). To ensure that the first-order translog parameters can be directly interpreted as the production elasticities at the sample median firm, all parameters are divided by its median value, thereby this does not change the results (see e.g. Coelli et al., 2005). The translog output distance function for $K(k = 1, ..., K)$ inputs and $M(m = 1, ..., M)$ outputs can be written for panel data as:

$$\begin{aligned} lnD^O_{it} = \alpha_0 + \sum_{m=1}^{M} \alpha_m lnq_{mit} + \frac{1}{2} \sum_{m=1}^{M} \sum_{n=1}^{M} \alpha_{mn} lnq_{mit} * lnq_{nit} \\ + \sum_{k=1}^{K} \beta_k lnx_{kit} + \frac{1}{2} \sum_{k=1}^{K} \sum_{l=1}^{K} \beta_{kl} lnx_{kit} * lnx_{lit} \\ + \sum_{k=1}^{K} \sum_{m=1}^{M} \eta_{km} lnq_{kit} * lnx_{mit} + \sum_{s=1}^{S} \gamma_s z_{sit} \end{aligned} \quad (3)$$

where $lnD^O_{i,t}$ is the output distance term with the subscript $i = 1, ..., I$ for the ith-firm in year $t = 1, ..., T$. x_{kit} and q_{mit} denote the input and output quantity, respectively. $z_{sit}(z = 1, ..., S)$ reflects a vector of observable firm-specific factors expected to have an impact on the production technology; and α, β, η, and γ are unknown parameters to be estimated.

In order to ensure the theoretical conditions of symmetry and linear homogeneity of degree one in outputs, it is necessary to impose some restrictions that must be hold by the output distance function (see e.g. Coelli and Perelman, 2000): For symmetry it is required $\alpha_{mn} = \alpha_{nm}$ for $m, n = 1, 2, ..., M$ and $\beta_{kl} = \beta_{lk}$ for $k, l = 1, 2, ..., K$. Linear homogeneity in degree one in outputs is given if $\sum_{m=1}^{M} \alpha m = 1$, $\sum_{n=1}^{M} \alpha_{mn} = 0$ for $m = 1, 2, ..., M$ and $\sum_{m=1}^{M} \beta_{mk} = 0$ for $k, l = 1, 2, ..., K$. Following Lovell et al. (1994) the homogeneity restrictions can be imposed through normalizing the distance term and the outputs by choosing arbitrarily one of the outputs such as q_M.[2] Hence, the dependent variable in Equation 3 becomes lnD^O_{it}/q_{Mit} which can be rewritten as

[2] The symmetry restrictions are done during estimation.

$ln(D^O_{it}) - ln(q_{Mit})$. It enables us to express the formulation as a standard production frontier since the distance term, $ln(D^O_{it})$, can be transfered to the right-hand side of Equation 3. Replacing the negative log of the distance term with the inefficiency term, as they are equivalent, (i.g. $-lnD = -u$), yields the common form of a stochastic frontier estimation:

$$\begin{aligned} lnq_{Mit} = \alpha_0 + \sum_{m=1}^{M-1} \alpha_m lnq^*_{mit} + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M} \alpha_{mn} lnq^*_{mit} * lnq^*_{nit} \\ + \sum_{k=1}^{K} \beta_k lnx_{kit} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} lnx_{kit} * lnx_{lit} \\ + \sum_{k=1}^{K}\sum_{m=1}^{M-1} \eta_{km} lnx_{mit} * lnq^*_{mit} + \sum_{s=1}^{S} \gamma_s z_{sit} + \nu_{it} - u_{it} \end{aligned} \tag{4}$$

where summations over m implies summing only the $M-1$ outputs not used for normalization, since $q^*_{mit} = (q_{mit}/q_{Mit})$ thus $q^*_{mit} = 1$.[3] Due to the fact that it is more consistent with the expected signs of parameters in conventional production frontiers, we follow studies that use $ln(q_{Mit})$ as dependent variable instead of $-ln(q_{Mit})$ (see e.g., Paul et al., 2000; Pascoe, 2010; Abbott and Doucouliagos, 2009).[4]

4 Modeling approach

In order to estimate the effect of competitive funding on the universities' production frontier and efficiency our analyses are based on a simultaneous SFA approach, in which the production model and the technical inefficiency model are jointly estimated. In particular, the impact of exogeneous determinants on the production frontier and on the inefficiency term are estimated simultaneously. Therewith, we consider the criticism of the two-stage approach used in the past which lacks the fact that the second stage analysis of systematic determinants of the inefficiency effects contradicts the assumption of

[3]In the single output case, where $M = 1$ is used in the production process, the output distance function will be equivalent to a standard output translog production function.

[4]Note that for estimation purposes, the negative sign on the dependent variable can be ignored, but it makes the interpretation of the estimated coefficients easier (Paul et al., 2000).

an identical distribution of these effects that is made in the first stage, when the stochastic frontier is estimated.

Following the framework developed in Section 2, we firstly include the budget shares financed by tuition fees, international public funds, and private funds in the stochastic output distance function. Using the budget share variables as explanatory variables in the distance function directly suggests the interpretation that funding competition affects the production frontier itself. Disregard the translog output distance function formulation but following the stochastic frontier approach we can easily write:

$$q_{Mit} = \alpha_0 + \alpha' q_{it} + \beta' x_{it} + \gamma_s BSHA_{it} + \nu_{it} - u_{it} \tag{5}$$

where q_{Mit} serves as normalizing output and is used as dependent variable, $\alpha' q_{it}$ contains the vector of normalized outputs and $\beta' x_{it}$ reflects the production technology of the i-th university in time, t. The Z-variables from Equation 4 are specified by introducing the vector $BSHA_{it}$, which covers the budget shares of the third-party variables which are assumed to influence the university production frontier. Again, ν_{it} and u_{it} are the two components of the disturbance error term, ϵ_{it}.

Arguably, university management controls the shares of third-party funding by introducing corresponding incentives, implying that the funding shares influence efficiency but not the production frontier. In this case the proper econometric strategy consists of modeling efficiency as a function of the funding shares, but refrain from including them in the output distance function directly (see e.g. Cherchye and Abeele, 2005). However, to the extent that competition pressures universities at the boundary to increase their effort, the estimated production frontier might shift as well. Examples for the treatment of funding structure as exogenous are Bonaccorsi et al. (2006) and Carayol and Matt (2006).

For our analyses, we therefore assume that the funding shares influence both the production frontier and the inefficiency of universities. By allowing the inefficiency term, u_{it}, to be a function of the third-party variables the inefficiency equation can then be written as:

$$q_{Mit} = \alpha_0 + \alpha' q_{it} + \beta' x_{it} + \gamma_s BSHA_{it} + \nu_{it} - u_{it}(BSHA_{it}) \tag{6}$$

whereas for our analyses u_{it} is to be assumed to follow a half-normal distribution, i.i.d. $(u_{it}\ N^{+}[0, \sigma_u^2])]$.[5]

Furthermore, in order to allow the inefficiency not to be homogeneous across individuals and time, quite a few models are proposed recently which incorporate several forms of heterogeneity in the inefficiency model.[6] In particular, traditional SFA models suggest that firms operate under the same production technology and that the inefficiency distribution across individuals and time are homogeneous; hence, firms are to be assumed only differing by the random noise term.

In order to account for exogeneous determinants affecting the inefficiency one may e.g. follow Battese and Coelli (1995) who assumed for the inefficiency model that the mean of the inefficiency term, μ_{uit}, is a linear function of firm-specific attributes, z_{it}, which directly affect technical inefficiency, i.i.d.$(u_{it}\ N^{+}[\mu_{it}, \sigma_u^2])$. However, we follow Caudil et al. (1995), who incorporated heterogeneity in the variance of u_{it}, allowing for heteroscedasticity, an assumption which is due to the SFA models proposed by Reifschnieder and Stevenson (1991) and by Simar and van den Eeckhaut P. (1994).[7] In particular, Caudil et al. (1995) analyzed, whether the variance of the inefficiency term, u_{it}, is constant over the whole sample or influenced by some of the explanatory variables. They could show that the presence of heteroscedasticity yields biased parameter estimates of the production frontier and firm-specific inefficiency, i.g. the inefficiency term varies according to increasing inputs, since firms with a high input- and output-capacity have some scope for variation, and therefore scope for inefficiency.

Consequently, for the inefficiency equation we use the variance of the inefficiency term, u_{it}, modelled as a function of the third-party variables written as:

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[5] A half-normal distribution—together with the exponential—is the most widely used distribution to model inefficiency. Other distributional assumptions of u_i are e.g., the truncated normal or gamma distribution.

[6] Basically, they focus on a differentiation between heterogeneity in the production model and heterogeneity in the inefficiency model, or a differentiation between observable and unobservable heterogeneity (Greene, 2008).

[7] Reifschnieder and Stevenson (1991) developed (but does not implement) a model in which the standard deviation parameter of inefficiency is a function of firm specific conditions, while Simar and van den Eeckhaut P. (1994) formulate a model in which the variance and the mean of inefficiency depends on a set of firm characteristics via a scale transformation of the inefficiency term.

$$\sigma_{u_{it}}^2 = \psi_0 + \delta_r BSHA_{rit} + \omega_{it} \tag{7}$$

whereas $BSHA_{rit}$ is the vector of the explanatory variables—the budget shares financed by tuition fees public international funds and private funds—and δ_r is a parameter vector to be estimated that captures the influence of the explanatory determinants on the level of inefficiency. Given that the inefficiency term is assumed to follow a half-normal distribution, a decrease in the variance will lead to increments in the efficiency level; i.g. a positive (negative) coefficient estimate of δ_r indicates a negative (positive) effect on the variance of technical efficiency. ω_{it} refers to the standard normally distributed error term. In this approach, the parameters for the production frontier and for the inefficiency model are estimated jointly using the maximum likelihood technique (Caudil et al., 1995). Furthermore, the variance and the mean of the inefficiency term have a linear relationship, i.e. if one goes up, so does the other.

The above methodology captures our attempt to disentangle correlations between third-party funding, the production frontier and efficiency. However, there are a number of reasons why the observed correlation might not reflect causality. An example includes the potential of reverse causality, i.e. the possibility that third-party funding goes to efficient universities and not the other way round. Unobserved heterogeneity, e.g. student and staff quality causes identification problems as well. We attempt to exploit the panel data structure to address these problems of identification. Notably, in order to account for country specific differences we include country dummies to tackle unobserved heterogeneity at country level. We also incorporate country averages to control on the one hand for reverse causality and on the other hand for unobserved heterogeneity at university level assuming that third-party funding is not affected by a single university, instead it is rather a political decision process exogenously given. Finally, we have included lagged values of budget shares of two years to control for reverse causality, and year dummies to account for differences over time.

5 Data issues and empirical model

The data used in this study stems from the Aquameth database, a European project that has established an extensive data set which contains comparable statistics at university-level across a large number of European countries. The data are unbalanced and covers a period from 1994 to 2006. Detailed information on the Aquameth project and its database can be found in Bonaccorsi and Daraio (2007) and Daraio et al. (2011).[8]

Due to the issue of data availability we use data of Finland, Italy, Netherlands, Norway, Portugal, Spain, Switzerland and the UK four our analyses.[9] We use information on enrolled Bachelor's and Master's students to capture teaching output of the universities. The number of publications reflects the output of research. Five labor categories serve as inputs; they are professors, assistant professors, researchers, other administrative staff and finally technical and administrative staff. Note that despite all efforts, the definition of input variables varies across countries. Most notably, not all countries report full-time equivalent employment contracts. However, we follow Slipersaeter et al. (2005) and use a mix of FTE and headcount data of the university personnel. Furthermore, the labor categories appear somewhat fuzzy as well.

Moreover, the data includes detailed information on financial resources of each university; i.g. the shares of total budget financed by tuition fees, international public funds and private funds. Again, the usefulness of these variables varies substantially, where tuition fees present the largest problem. Norway and Finland do not have any tuition fees and in the remaining countries, the process of raising fees is strongly regulated. As a consequence, there is little variation over time. This feature collides with the fact that this study utilizes the panel structure of the data to establish a credible identification strategy. Both international public funds and private funds contain enough variation over time to render the argument above irrelevant.

For our analyses we manipulate the data in a number of ways: First, we interpolate all variables linearly and drop all observations with missing values. We also exclude all observations where data on the budget shares financed by international public grants or private funding are not available. Furthermore, we eliminate observations for which all outputs are missing. Finally, we replace outputs and inputs (and the budget share of tuition fees) by 0.01 (0), thereby allow for specialization of universities. In addition, all variables are normalized by the median.

The summary statistics of the variables is given in Table 2. Both the outputs, inputs as well as the budget shares cover a wide range of data values

[8] see `http://www.prime-noe.org/aquameth.html`

[9] As quality data of the universities in our sample are not available as much as needed quality indicators could not be included in the analyses.

with respect e.g., to country size (number of universities, number of students, labor inputs) and the political system of tertiary education (introduction of tuition fees, public and private budgets). Cross-correlations presented in Table 7 given in the Appendix indicates that inputs and outputs are correlated to some extent with each other.

Table 2: *Summary statistics for variables of the output distance function*

Variable	Variable description	Mean	Std. Dev.	Min	Max
q1*	Publications	774	1043	1	6964
q2**	Enrolled students	17935	20499	0	176154
x1*	Professors and assistant professors	648	817	0	6080
x2*	Other research staff	771	850	0	6295
x3*	Technical and administrative staff	904	727	38	6677
bsha_tuit*	Budget share of tuition fees	0.1871	0.1101	0	0.7042
bsha_pub_int*	Budget share of international public funds	0.0228	0.0230	0	0.5499
bsha_priv*	Budget share of private funds	0.0471	0.0639	0	0.4020

*enters in logs, normalized by median; **enters in logs, normalized by median and publications

Number of observations: 1711 (1994-2004)

The output distance function we use for our analyses has then the following functional form:

$$
\begin{aligned}
lnQ_{1ijt} = \alpha_0 + \alpha_1(ln(Q_{2ijt}/Q_{1ijt})) + \frac{1}{2}\alpha_{11}(ln(Q_{2ijt}/Q_{1ijt}))^2 \\
+\beta_1 lnX_{1ijt} + \beta_2 lnX_{2ijt} + +\beta_3 lnx_{3ijt} \\
+\frac{1}{2}\beta_{11}(lnX_{1ijt})^2 + \frac{1}{2}\beta_{22}(lnX_{2ijt})^2 + \frac{1}{2}\beta_{33}(lnX_{3ijt})^2 \\
+\beta_{12} lnX_{1ijt} * lnX_{2ijt} + \beta_{13} lnX_{1ijt} * lnX_{3ijt} + \beta_{23} lnX_{2ijt} * lnX_{3ijt} \\
+\eta_{12} lnX_{1ijt} * lnQ_{2ijt} + \eta_{22} lnX_{2ijt} * lnQ_{2ijt} + \eta_{32} lnX_{3ijt} * lnQ_{2ijt} \\
+\gamma_1 BSHA_{tuitFijt} + \gamma_2 BSHA_{pubintFijt} + \gamma_3 BSHA_{privFijt} \\
+\nu_{ijt} + u_{ijt} + \sum_{c=1}^{C} \delta_c Control_{cijt}.
\end{aligned}
\tag{8}
$$

whereas the number of publications, Q_1, of university i in country j in time t is the dependent variable and serves as the normalizing output. The remaining output, i.g. the number of enrolled Bachelor and Master students appears as explanatory variable normalized by publications, Q_2/Q_1. The labor input variables are denoted by X_1, X_2, X_3, and the external variables,

$BSHA$, that reflect the budget shares financed by tuition fees, public international funds and private funds are respectively displayed with the subscript $tuitF$, $pubintF$, $privF$. ν_{ijt} corresponds to the normally distributed error term, and u_{ijt} refers to the inefficiency term. The vector of control variables, $Control$, covers several dummy variables to tackle unobserved heterogeneity and reverse causality in our analyses.

6 Results

Table 3 and Table 4 displays the results for the different model specifications based on distance function analyses.[10] All estimations refer to a simultaneous two-stage SFA, meaning the production model is jointly estimated with the inefficiency model while assuming a half-normal distribution with the variance of inefficiency as dependent variable. The four models differ with respect to the inclusion of control variables; i.g. year dummies, country dummies, lagged values of budget shares and country averages. Therewith, it allows us to account for reverse causality and unobserved heterogeneity at country level and university-level.

First of all, focusing on the distance function estimates displayed in the upper part of Table 3 our results show that the coefficients are well-behaving in the sense that the first-order coefficients are statistically significant at the 1 percent level, and they have the expected signs across all four models. That means the coefficient of the output variable is negative, while the coefficients of the input variables are positive. However, the magnitude of the coefficients differs slightly across the models, which is especially true when comparing Model I, the basic model specification, with Model II, III, and IV in which we account for reverse causality and unobserved heterogeneity. The smallest difference among the models' coefficients is given between Models II and III.

Our results regarding the effects of the budget shares on the production frontier can be seen in the lower part of Table 3 which provides the coefficients of third-party variables of the simultaneous first-stage stochastic frontier estimations. For tuition fees the coefficients across nearly all four models are positive and highly statistically significant, which indicates, as we predicted, a kind of sorting effect. An increase in tuition fees rises the production frontier of the best performing universities; it is shifted outwards. Also for international public funds we found a highly significant,

[10]Please find the results entire displayed in Table 5 given in the Appendix.

Table 3: *SFA and endogeneity: production model*

	Model 1	Model 2	Model 3	Model 4
depvar: publ. (q1)	**Production Frontier**			
q2 (students)	-0.615***	-0.705***	-0.704***	-0.618***
	(0.000)	(0.000)	(0.000)	(0.000)
$q2^2$	-0.079***	-0.085***	-0.088***	-0.081***
	(0.000)	(0.000)	(0.000)	(0.000)
x1 (professors)	0.416***	0.384***	0.383***	0.429***
	(0.000)	(0.000)	(0.000)	(0.000)
x2 (other res. staff)	0.273***	0.366***	0.359***	0.349***
	(0.000)	(0.000)	(0.000)	(0.000)
x3 (tech. and adm. staff)	0.290***	0.213***	0.204***	0.206***
	(0.000)	(0.000)	(0.000)	(0.000)
$x1^2$	0.056***	0.054***	0.015	0.021
	(0.000)	(0.000)	(0.527)	(0.516)
$x2^2$	0.017***	0.016**	0.004	0.015**
	(0.004)	(0.015)	(0.485)	(0.041)
$x3^2$	0.194***	-0.017	0.045	0.050
	(0.000)	(0.703)	(0.487)	(0.427)
x1x2	-0.046***	-0.106***	-0.111***	-0.082***
	(0.001)	(0.000)	(0.000)	(0.000)
x1x3	-0.032**	0.043**	0.051**	0.041
	(0.046)	(0.023)	(0.036)	(0.223)
x2x3	-0.044**	0.042**	0.028	-0.016
	(0.036)	(0.024)	(0.172)	(0.471)
x1q2	-0.008***	-0.016***	-0.054***	-0.056**
	(0.009)	(0.000)	(0.007)	(0.011)
x2q2	-0.103***	-0.119***	-0.163***	-0.146***
	(0.000)	(0.000)	(0.000)	(0.000)
x3q2	0.132***	0.129***	0.202***	0.186***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_tuit	0.214***	0.522***	0.442***	0.197*
	(0.000)	(0.000)	(0.000)	(0.094)
bsha_tuit^2	0.119***	0.201***	0.160***	0.105*
	(0.000)	(0.000)	(0.000)	(0.065)
bsha_pub_int	-0.118***	-0.089***	-0.093***	-0.319***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_pub_int^2	-0.023**	-0.016**	-0.031***	-0.082
	(0.021)	(0.048)	(0.001)	(0.474)
bsha_priv	0.057**	0.017	0.010	0.044
	(0.011)	(0.324)	(0.606)	(0.417)
bsha_priv^2	-0.027**	-0.032***	-0.045***	0.138
	(0.021)	(0.000)	(0.000)	(0.182)
Constant	0.228***	-0.173***	-0.191**	0.351***
	(0.000)	(0.010)	(0.040)	(0.000)
N	1711	1711	1280	1297
Year dummies	yes	yes	yes	yes
Country dummies	no	yes	yes	no
Lagged values	no	no	yes	yes
Country averages	no	no	no	yes

p-values of coefficients in parentheses; *, ** and *** denote significance levels 10%, 5% and 1%.

though, negative effect on the universities' production frontier. This finding gives strong evidence for an administration or misallocation effect—we cannot differentiate them. The negative coefficients reported for international public funds support our hypothesis that misspecified restrictions on the use of third-party funds caused by incomplete information reduce the production frontier. Furthermore, the results imply an administration effect mainly caused by monitoring costs which reduce the production frontier. Especially applying for international public funds, e.g. funds announced by the European Commission, is time-consuming. In other words, to follow the formal requirements means that the researcher's time available for teaching and research activities decreases. Unlike tuition fees and international public funds, the coefficients of the linear terms of the private funds estimates generally show no significant values. Though, we find for almost all squared terms highly significant coefficients, which would suggest an inverse u-shaped effect of private funds on the production frontier of universities. However, these results persist ambiguous.

Table 4: *SFA and endogeneity: efficiency model*

	Model 1	Model 2	Model 3	Model 4
depvar: σ_u^2	**Inefficiency Equation**			
bsha_tuit	1.073***	2.140***	1.789***	3.862***
	(0.000)	(0.000)	(0.000)	(0.001)
bsha_tuit^2	1.022***	1.429***	1.090***	3.655***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_pub_int	-0.799***	-0.935***	-0.744***	-2.277***
	(0.002)	(0.000)	(0.006)	(0.000)
bsha_pub_int^2	-0.189	-0.227	-0.404**	-1.264***
	(0.154)	(0.112)	(0.015)	(0.003)
bsha_priv	0.210	0.474*	0.448**	7.929***
	(0.404)	(0.066)	(0.019)	(0.000)
bsha_priv^2	-0.749***	-0.902***	-0.674***	-9.998***
	(0.000)	(0.001)	(0.000)	(0.000)
Constant	-1.587***	-2.010***	-1.607***	-2.794***
	(0.000)	(0.000)	(0.000)	(0.000)
N	1711	1711	1280	1297
Year dummies	yes	yes	yes	yes
Country dummies	no	yes	yes	no
Lagged values	no	no	yes	yes
Country averages	no	no	no	yes

p-values of coefficients in parentheses; *, ** and *** denote significance levels 10%, 5% and 1%.

The effects on university efficiency is displayed in Table 4 which gives the results of the simultaneous second stage coefficients estimated with the variance of inefficiency as dependent variable. For tuition fees we find positive and statistically significant coefficients at the 1 percent level across all four models. This findings imply that a rise of tuition fees increases inefficient vice versa decreases efficient production of universities. Indeed, it gives evidence for a sorting effect: Though the efficiency of the best performing universities may increases, the spread of efficient and inefficient operating universities rises. Consequently, the average efficiency across all universities decreases. Furthermore, the results of the linear terms of international public funds show highly significant negative coefficients implying a positive impact on university efficiency. Following our predictions this result gives evidence for a discipline effect as an increasing competition of funding sources increases efficient production. One may suggest, e.g. that researchers only apply for third-party funds, whom efforts will be reasonable compared to funding requirements and project accomplishment. Finally, we also find ambiguous effects of private funds on university efficiency as the squared term shows highly significant negative estimates. Again, this result indicates an inverse u-shaped effect on the efficiency.

In order to evaluate the robustness of our results, Table 6 in the Appendix reports six additional specifications, whereas Model IV repeat the estimates of Model II in Table 3 and 4. The remaining columns show different models which allows us to control for multicollinearity of variables and estimation stages. In the first three columns the Model I-III include budget shares financed by tuition fees, international public funds and private funds separately in both frontier and inefficiency equation. In Model VI and VII all budget shares types are included only in the frontier equation and only in the inefficiency equation, respectively. Moreover, Model VII is run including all budget shares types in both equations but adding their interactions with x and q in the frontier equation. We find that our results remain qualitatively robust to these variations in the model specification.

7 Conclusion

In our study we estimated the impact of competitive university funding, suggesting that the direction of the effect might differ between the production frontier and efficiency. We tested the models predictions using an unbalanced panel data set at micro-level across 8 European countries to estimate a simultaneous two-stage SFA. Our analyses show mixed results for the effect of third-party funding on university production. For tuition fees we found a positive impact on the production frontier, but a negative one on efficiency which supports a kind of sorting effect. For international public funds we find strong evidence for the administrative effect as the estimates correlate negatively with the production frontier. Moreover, our findings give evidence for a misallocation effect and a discipline effect which is consistent with the hypotheses, that competitive funding reduces the frontier due to monitoring costs, but increases competition and therefore decreases inefficiency. The results for private funds are ambiguous as indicated by an inverse u-shaped effect on both the production frontier and efficiency. Our results suggest that introducing competition in the university sector entails a trade-off that should be taken into account by politicians.

References

Abbott, Malcolm and Chris Doucouliagos (2009), 'Competition and efficiency: overseas students and technical efficiency in Australian and New Zealand universities', *Education Economics* **17**(1), 31–57.

Aghion, P., M. Dewatripont, C. M. Hoxby, A. Mas-Colell and A. Sapir (2009), 'The governance and performance of research universities: Evidence from europe and the u.s', *NBER Working Paper 14851* .

Aigner, D., C.A. Knox Lovell and P. Schmidt (1977), 'Formulation and estimation of stochastic frontier production models', *Journal of Econometrics* **6**, 21–37.

Auranen, O. and M. Nieminen (2010), 'University research funding and publication performance—an international comparison', *Research Policy* **39**, 822–834.

Battese, G E and T J Coelli (1995), 'A model for technical inefficiency effects in a stochastic frontier production function for panel data', *Empirical Economics* **20**(2), 325–32.

Black, D. A. and J.A. Smith (2004), 'How robust is the evidence on the e ects of college quality? evidence from matching', *Journal of Econometrics* **121**, 99 – 124.

Bonaccorsi, A. and C. Daraio, eds (2007), *Universities and Strategic Knowledge Creation. Specialization and Performance in Europe*, Edward Elgar ,Cheltenham.

Bonaccorsi, A., C. Daraio and L. Simar (2006), 'Advanced indicators of productivity of universities: An application of robust nonparametric methods to Italian data', *Scientometrics* **66(2)**, 389–410.

Butler, Linda (2003), 'Explaining australia's increased share of isi publications–the effects of a funding formula based on publication counts', *Research Policy* **32**(1), 143–155.

Carayol, Nicolas and Mireille Matt (2006), 'Individual and collective determinants of academic scientists' productivity', *Information Economics and Policy* **18**(1), 55–72.

Caudil, Steven B., Jon M. Ford and Daniel M. Gropper (1995), 'Frontier estimation and firm-specific inefficiency measures in the presence of heteroscedasticity', *Journal of Business & Economic Statistic* **13(1)**, 105–111.

Cherchye, L. and P. Vanden Abeele (2005), 'On research efficiency: A microanalysis of dutch university research in economics and business management', *Research Policy* **34**(4), 495–516.

Coelli, T. J. (2000), 'On the econometric estimation of the distance function representation of a production technology', *Universit ´e Catholique de Louvain - Center for Operations Research and Economics, Louvain-la-Neuve, Belgium.* .

Coelli, T. J. and S. Perelman (2000), 'Technical efficiency of european railways: A distance function approach', *Applied Economics* **32(15)**, 1967–1976.

Coelli, T.J., D.S.P. Rao, C.J. O'Donnell and C.E. Battese (2005), *An introduction to efficiency and productivity analysis*, 2nd edn, Springer.

Cook, P. J. and R. H. Frank (1993), *Studies of Supply and Demand in Higher Education*, University of Chicago Press, chapter The Growing Concentration of Top Students at Elite Schools, pp. 121–144.

Coupé, T., V. Smeets and F. Warzynski (2003), Incentives in economic departments: Testing tournaments?, Technical report, ISSN 1397-4831, Working Paper 03 -25, Department of Economics of Aarhus School of Business.

Daraio, Cinzia, Andrea Bonaccorsi, Aldo Geuna, Benedetto Leporic, Laurent Bach, Peter Bogetoft, Margarida F. Cardoso, Gustavo Crespi Elena Castro-Martinez, Ignacio Fernandez de Lucio, Harold Fried, Adela Garcia-Aracil, Annamaria Inzelt, Ben Jongbloed, Gerhard Kempkes, Patrick Llerena, Mireille Matt, Maria Olivares, Carsten Pohl, Tarmo Raty, Maria J.Rosas, Cláudia S. Sarrico, Léopold Simar, Stig Slipersaetern, Pedro N. Teixeira and Philippe Vanden Eeckaut (2011), 'The european university landscape:a micro characterization based on evidence from theaquameth project', *ResearchPolicy* **40**, 148–164.

Färe, R. and D. Primont (1995), *Multi-output Production and Duality: Theory and Applications.*, Kluwer Academic Publishers, Boston.

Fried, H., K. Lovel and S. Schmidt, eds (2008), *The measurement of Productive Efficiency and Productitiy Growth*, Oxford University Press.

Greene, W. H. (2008), *The Measurement of Productive Efficiency*, Oxford University Press, Oxford., chapter The econometric approach to efficiency measurement, pp. 68–119.

Kempkes, G. and C. Pohl (2008), 'The efficiency of German universities - some evidence from non-parametric and parametric methods', *Applied Economics* **Online First**.

Kivistö, J. (2005), 'The government-higher education institution relationship: Theoretical considerations from the perspective of agency theory', *Tertiary Education and Management* **11**, 1–17.

Kuo, H.S. and Y.C. Ho (2007), 'The cost efficiency impact of the university operation fund on public universities in taiwan', *Economics of Education Review* **27**, 603–612.

Laudel, G. (2006), 'The art of getting funded: how scientists adapt to their funding conditions', *Science and Public Policy,* **33(7)**, 489–504.

Lovell, C. A. K., S. Richardson, P. Travers and L. L. Wood (1994), *Models and Measurement of Welfare and Inequality*, Springer Verlag, Berlin, chapter Resources and functionings: a new view of inequality in Australia, p. 787–807.

Meeusen, W. and J. van den Broeck (1977), 'Efficiency estimation from cobb-douglas production functions with composed error', *International Economic Review* **18**, 435–444.

Mensah, Yaw M. and Robert Werner (2003), 'Cost efficiency and financial flexibility in institutions of higher education', *Journal of Accounting and Public Policy* **22**(4), 293–323.

Niskanen, W.A. (1971), *Bureaucracy in representative government*, Aldine-Atherton, New York.

Niskanen, W.A. (1975), 'Bureaucrats and politicians', *Journal of Law and Economics* **18(3)**, 617–643.

Pascoe, S. Punt, A.E. Dichmont C.M. (2010), 'Targeting ability and output controls in australia's multi-species northern prawn fishery', *European Review of Agricultural Economics* **37(3)**, 313–334.

Paul, C. J., W. E. Johnston and G. A. Frengley (2000), 'Efficiency in new zealand sheep and beef farming: The impacts of regulatory reform', *The Review of Economics and Statistics* **82 (2)**, 325–337.

Reifschnieder, D. and R. Stevenson (1991), 'Systematic departures from the frontier: a framework for the analysis of firm inefficiency', *International Economic Review* **32(3)**, 715–723.

Schiller, D. and I. Liefner (2006), 'Higher education funding reform and university-industry links in developing countries: The case of thailand', *Higher Education* **54**, 543–556.

Schubert, T. (2009), 'Empirical observations on new public management to increase efficiency in public research—boon or bane?', *Research Policy* **38**, 1225–1234.

Shephard, R. W. (1953), *Cost and Production Functions*, Princeton University Press, Princeton, New Jersey.

Shephard, R. W. (1970), *Theory of Cost and Production Functions*, Princeton University Press, Princeton, New Jersey.

Simar, L., Lovell K. and van den Eeckhaut P. (1994), 'Stochastic frontiers incorporating exogenous influences on efficiency', *Discussion Paper No. 0317, Institut de Statistique, Universit´e Catholique de Louvain, Louvain-la-Neuve, Belgium* .

Slipersaeter, Stig, Benedetto Lepori, Ben Jongbloed and Carlo Salerno (2005), Collecting institutional level data from european higher education institutions: evidence from chinc countries an interim report for the project changes in university incomes: Their impact on university-based research and innovation (chinc), Technical report, CHEPS.

Van der Meulen, B. (1998), 'Science policies as principal–agent games institutionalization and path dependency in the relation between government and science', *Research Policy* **27**, 397–414.

Van der Ploeg, F. and R. Veugelers (2008), 'Towards evidence-based reform of european universities', *CESifo Economic Studies* **54**(2), 99–120.

Appendix

Table 5: *SFA and Endogeneity*

	Model 1	Model 2	Model 3	Model 4
Production Frontier: depvar: publ. (q1)				
q2 (students)	-0.615***	-0.705***	-0.704***	-0.618***
	(0.000)	(0.000)	(0.000)	(0.000)
$q2^2$	-0.079***	-0.085***	-0.088***	-0.081***
	(0.000)	(0.000)	(0.000)	(0.000)
x1 (professors)	0.416***	0.384***	0.383***	0.429***
	(0.000)	(0.000)	(0.000)	(0.000)
x2 (other res. staff)	0.273***	0.366***	0.359***	0.349***
	(0.000)	(0.000)	(0.000)	(0.000)
x3 (tech. and adm. staff)	0.290***	0.213***	0.204***	0.206***
	(0.000)	(0.000)	(0.000)	(0.000)
$x1^2$	0.056***	0.054***	0.015	0.021
	(0.000)	(0.000)	(0.527)	(0.516)
$x2^2$	0.017***	0.016**	0.004	0.015**
	(0.004)	(0.015)	(0.485)	(0.041)
$x3^2$	0.194***	-0.017	0.045	0.050
	(0.000)	(0.703)	(0.487)	(0.427)
x1x2	-0.046***	-0.106***	-0.111***	-0.082***
	(0.001)	(0.000)	(0.000)	(0.000)
x1x3	-0.032**	0.043**	0.051**	0.041
	(0.046)	(0.023)	(0.036)	(0.223)
x2x3	-0.044**	0.042**	0.028	-0.016
	(0.036)	(0.024)	(0.172)	(0.471)
x1q2	-0.008***	-0.016***	-0.054***	-0.056**
	(0.009)	(0.000)	(0.007)	(0.011)
x2q2	-0.103***	-0.119***	-0.163***	-0.146***
	(0.000)	(0.000)	(0.000)	(0.000)
x3q2	0.132***	0.129***	0.202***	0.186***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_tuit	0.214***	0.522***	0.442***	0.197*
	(0.000)	(0.000)	(0.000)	(0.094)
bsha_tuit^2	0.119***	0.201***	0.160***	0.105*
	(0.000)	(0.000)	(0.000)	(0.065)
bsha_pub_int	-0.118***	-0.089***	-0.093***	-0.319***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_pub_int^2	-0.023**	-0.016**	-0.031***	-0.082
	(0.021)	(0.048)	(0.001)	(0.474)
bsha_priv	0.057**	0.017	0.010	0.044
	(0.011)	(0.324)	(0.606)	(0.417)
bsha_priv^2	-0.027**	-0.032***	-0.045***	0.138
	(0.021)	(0.000)	(0.000)	(0.182)
Constant	0.228***	-0.173***	-0.191**	0.351***
	(0.000)	(0.010)	(0.040)	(0.000)
Inefficiency Equation: depvar: σ_u^2				
bsha_tuit	1.073***	2.140***	1.789***	3.862***
	(0.000)	(0.000)	(0.000)	(0.001)
bsha_tuit^2	1.022***	1.429***	1.090***	3.655***
	(0.000)	(0.000)	(0.000)	(0.000)
bsha_pub_int	-0.799***	-0.935***	-0.744***	-2.277***
	(0.002)	(0.000)	(0.006)	(0.000)

	Model 1	Model 2	Model 3	Model 4
bsha_pub_int^2	-0.189	-0.227	-0.404**	-1.264***
	(0.154)	(0.112)	(0.015)	(0.003)
bsha_priv	0.210	0.474*	0.448**	7.929***
	(0.404)	(0.066)	(0.019)	(0.000)
bsha_priv^2	-0.749***	-0.902***	-0.674***	-9.998***
	(0.000)	(0.001)	(0.000)	(0.000)
Constant	-1.587***	-2.010***	-1.607***	-2.794***
	(0.000)	(0.000)	(0.000)	(0.000)
N	1711	1711	1280	1297
Year dummies	yes	yes	yes	yes
Country dummies	no	yes	yes	no
Lagged values	no	no	yes	yes
Country averages	no	no	no	yes

p-values of coefficients in parentheses; *, ** and *** denote significance levels of 10%, 5% and 1%. All estimations refer to a simultaneous two-stage SFA, the first stage, the production function estimation, and in the second stage with the inefficiency estimation assuming a half-normal distribution with the variance of inefficiency as dependent variable. Model 1: Basic estimation, Model 2: Including country dummies, Model 3: Including country dummies and lagging budget shares by two years, Model 4: Using country averages of budget shares lagged by two years.

Table 6: *SFA and Multicollinearity*

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Production Frontier: depvar: publ. (q1)							
q2	-0.664***	-0.639***	-0.624***	-0.705***	-0.606***	-0.661***	-0.671***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$q2^2$	-0.084***	-0.080***	-0.083***	-0.085***	-0.081***	-0.083***	-0.091***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
x1	0.398***	0.367***	0.351***	0.384***	0.368***	0.329***	0.401***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
x2	0.379***	0.373***	0.398***	0.366***	0.392***	0.407***	0.331***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
x3	0.206***	0.242***	0.246***	0.213***	0.233***	0.246***	0.213***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$x1^2$	0.072***	0.055***	0.053***	0.054***	0.058***	0.050***	0.061***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$x2^2$	0.007	0.011	0.017	0.016**	0.016	0.010	0.015*
	(0.311)	(0.336)	(0.217)	(0.015)	(0.221)	(0.364)	(0.051)
$x3^2$	-0.002	0.048	0.074	-0.017	0.050	0.020	0.003
	(0.964)	(0.352)	(0.153)	(0.703)	(0.388)	(0.690)	(0.952)
x1x2	-0.120***	-0.108***	-0.107***	-0.106***	-0.116***	-0.120***	-0.083***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
x1x3	0.043	0.027	0.032*	0.043**	0.039*	0.050**	0.044**
	(0.109)	(0.171)	(0.053)	(0.023)	(0.054)	(0.010)	(0.025)
x2x3	0.043**	-0.021	-0.026	0.042**	-0.007	-0.013	0.012
	(0.026)	(0.346)	(0.247)	(0.024)	(0.776)	(0.545)	(0.561)
x1q2	-0.019***	-0.003	-0.005	-0.016***	-0.006	-0.006	-0.010*
	(0.001)	(0.332)	(0.129)	(0.000)	(0.104)	(0.140)	(0.054)
x2q2	-0.154***	-0.175***	-0.182***	-0.119***	-0.161***	-0.199***	-0.140***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
x3q2	0.162***	0.150***	0.173***	0.129***	0.163***	0.161***	0.148***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
bsha_tuit	0.502***			0.522***		0.180***	0.463***
	(0.000)			(0.000)		(0.000)	(0.000)
bsha_tuit^2	0.169***			0.201***		0.005	0.175***
	(0.000)			(0.000)		(0.858)	(0.000)
bsha_pub_int		-0.125***		-0.089***		-0.050***	-0.064***
		(0.000)		(0.000)		(0.000)	(0.000)
bsha_pub_int^2		-0.027**		-0.016**		-0.012**	-0.032***
		(0.026)		(0.048)		(0.022)	(0.000)
bsha_priv			-0.034**	0.017		0.000	0.011
			(0.041)	(0.324)		(0.974)	(0.523)
bsha_priv^2			-0.044***	-0.032***		-0.008*	-0.013
			(0.000)	(0.000)		(0.066)	(0.214)
bsha_tuit_q2							0.056***
							(0.000)
bsha_tuit_x1							-0.055**
							(0.014)
bsha_tuit_x2							-0.008
							(0.738)
bsha_tuit_x3							0.045
							(0.104)
bsha_pub_int_q2							-0.050***
							(0.000)
bsha_pub_int_x1							-0.010
							(0.306)
bsha_pub_int_x2							-0.020*

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
							(0.077)
bsha_pub_int_x3							-0.022
							(0.195)
bsha_priv_q2							0.035***
							(0.000)
bsha_priv_x1							-0.009
							(0.380)
bsha_priv_x2							-0.008
							(0.420)
bsha_priv_x3							0.042**
							(0.017)
Constant	-0.153**	-0.702***	-0.646***	-0.173***	-0.606***	-0.415***	-0.412***
	(0.042)	(0.000)	(0.000)	(0.010)	(0.000)	(0.000)	(0.000)
Inefficiency Equation: depvar: σ_u^2							
bsha_tuit	1.672***			2.140***	0.351		1.765***
	(0.000)			(0.000)	(0.185)		(0.000)
bsha_tuit^2	1.053***			1.429***	0.383*		1.172***
	(0.000)			(0.000)	(0.080)		(0.000)
bsha_pub_int		-0.669***		-0.935***	-0.082		-0.741***
		(0.000)		(0.000)	(0.214)		(0.000)
bsha_pub_int^2		-0.176*		-0.227	0.049		-0.304**
		(0.076)		(0.112)	(0.577)		(0.011)
bsha_priv			-0.220**	0.474*	-0.151		-0.056
			(0.047)	(0.066)	(0.122)		(0.781)
bsha_priv^2			-0.488***	-0.902***	-0.224***		-0.756***
			(0.000)	(0.001)	(0.003)		(0.000)
Constant	-1.965***	-2.015***	-1.531***	-2.010***	-1.887***	-1.966***	-1.959***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
N	1711	1711	1711	1711	1711	1711	1711
Year dummies	yes	yes	yes	yes	yes	yes	yes
Country dummies	yes	yes	yes	yes	yes	yes	yes

p-values of coefficients in parentheses;*, ** and *** denote significance levels 10%, 5% and 1%
All estimations refer to a simultaneous two-stage SFA, the first stage, the production function estimation, and in the second stage with the inefficiency estimation assuming a half-normal distribution with the variance of inefficiency as dependent variable.
Model 1: Including budget share financed by tuition fees in both equations
Model 2: Including budget share financed by public international funds in both equations
Model 3: Including budget share financed by private funds in both equations
Model 4: Including all budget share types in both frontier and inefficiency equation
Model 5: Including all budget share types in the inefficiency equation only
Model 6: Including all budget share types in the frontier equation only
Model 7: Including all budget share types in both equations adding their interactions with x and q.

Table 7: *Cross-correlations between variables*

	q1	q2	x1	x2	x3	bsha_tuit	bsha_pub_int	bsha_priv
q1	1							
q2	0.0885	1						
x1	0.1868	0.6737	1					
x2	0.7485	0.0068	-0.022	1				
x3	0.6504	0.5096	0.4743	0.6656	1			
bsha_tuit	-0.272	0.1168	-0.065	-0.3415	-0.2041	1		
bsha_pub_int	0.0794	-0.0707	0.0385	-0.0354	-0.0197	-0.2074	1	
bsha_priv	0.3447	-0.2064	-0.1925	0.3387	0.1492	-0.517	0.2484	1